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What drives the development of renewable energy technologies? Toward a typology for the systemic drivers

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ABSTRACT

At present, governments are embarking on the ambitious undertaking of increasing their countries' market share of renewable energy. Political ambitions, however, are just one of the driving forces for energy companies' to engage in innovative climate projects. Energy companies' perceptions of business opportunities are dependent on a set of factors that influence their innovation ambitions. This research operationalizes previous work on the main drivers of the establishment of Renewable Energy Technologies (RETs), with the aim of presenting an overview of the typical systemic drivers within a technological innovation system (TIS) framework. This leads to the proposal of a comprehensive typology and categorization of drivers of RETs. The typology is validated empirically by analyzing data on the development of four types of RETs (wind, solar, biomass and wave energy) in eight European countries (EU-7 and Ireland). The study's results shed light on the multilateral drivers behind the development of RETs. Furthermore, a cross-case comparative study reveals the differences between drivers of RETs and the patterns of these drivers in different countries.

Contents

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1. Introduction

Energy markets have undergone profound changes over the past few decades. Depletable fossil fuels, growing concerns over climate change and catastrophic energy accidents such as the Fukoshima disaster are among the challenges that have raised awareness and prompted immediate action [1]. The introduction of renewable energy technologies into the energy system offers a possible solution. Though, even with supportive policies, RETs have experienced difficulties in entering into the market. Despite the double-digit growth rate of these emerging technologies since 1990, their progress has so far been "slow", "painful" and "highly uncertain" [2].

To boost the chances of success of such technological developments, politicians and governments have implemented a variety of initiatives. In 1997, the Kyoto protocol was among the first proactive political initiatives designed to trigger the development of RETs. This global agenda was just the beginning and has since been augmented by numerous political decisions on different levels. For instance, in Europe, policy makers have set the goal of achieving 20% total energy consumption from renewables by 2020 [3]. This target is supported by the roadmap to 2050, by which time the whole energy market should be decarbonized. To meet this ambitious target, however, political initiatives on their own are insufficient as drivers of RETs [1].

Factors that foster RETs (hereinafter, drivers) are defined as, *"the processes that influence trends and our ability to meet agreed-upon targets."*[1] [4: p. 8086]. Based on this definition, the role of drivers in accelerating and enhancing the innovation processes of RETs is significant. This is even truer if the intention is to influence a function of society [5]. Keeping this notion in mind, many scholars endeavor to understand the underlying RETs development processes so as to identify their drivers and barriers [6–8]. Nevertheless, while scholars have proposed comprehensive frameworks to describe the barriers of RETs development [9–11], the literature lacks inclusive studies that examinee drivers. Even still, a few studies that propose dispersed categories for the drivers are available [12–14], although findings and theories are inconsistent [15]. Given that the current aim to accelerate the development of RETs, this knowledge is essential to build a foundation primarily to exploit different drivers of future advances in renewable technologies, as well as to understand the effectiveness of each driver.

To address this research gap, the current study offers a comprehensive overview of the drivers of RETs, proposes a typology to classify these drivers, and then maps their significance with respect to different regions and technologies. The technological innovation system (TIS) framework offers a suitable theoretical basis to present and conceptualize a typology of drivers of RETs development. Academics have consistently deployed TIS as an appropriate framework, both theoretically and empirically, for studying advances in RETs [16]. Justification of the deployment of this framework lies in the slow and risky technological processes that energy companies must undergo [2]. Furthermore, energy companies have strong links to TIS elements (i.e., institutions) [6]. Researchers in this framework have shown that innovation processes are influenced by the environment [9]. Thus, innovation occurs as a result of technology and knowledge rather than the actions of one single actor [17].

Overall, the study aims to shed light on this unexplored area by answering the following main research questions.

1) *Which typologies of systemic technological innovation drivers are relevant for the development of renewable technologies*?
2) *How do these typologies relate to the level of maturity and the geographical features of each renewable technology*?

This study addresses these specific objectives by first presenting an in-depth literature review and then using secondary empirical data from the available research on RETs to perform descriptive empirical analysis. The findings serve two main purposes. Firstly, they provide insight into the formative phase of TIS by identifying main RETs drivers. Secondly, they contribute in mapping important drivers of the four types of RETs under study and their patterns in different countries.

The remainder of the paper has the following structure. Section 2 presents a review of prior studies on TIS and the main contributions of this approach to examining RETs systemic development. Section 3 outlines the study methodology step-by-step. Section 4 contains details about forming and conceptualizing a typology for drivers of RETs. In Section 5, a discussion of the study's results and findings appears, before Section 6 brings together the main conclusions and limitations of this research.

2. The contribution of TIS to understanding the RETs development

In the mid-1980s the concept of an innovation system (IS)—with an emphasis on the technology and information flow among people, enterprises and institutions—was developed as a key to understanding innovation processes [17]. IS emerged as a policy concept with a number of systemic dimensions [6]. Among these systemic dimensions, the use of a technology innovation system (TIS) framework to study and understand the emergence of a new technology has been widespread. A TIS has been defined as, "*a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and*

[1] Drivers have received other names such as "motivators", "driving forces", "ambitions" and "delivery factor" among others.

involved in the generation, diffusion, and utilisation of technology" [18: p. 93].

A TIS embodies the successful combination of hardware, software and orgware [19]. These structural elements include actors throughout the entire supply chain, institutions, networks and in some approaches technology [6]. Notably, whereas authors denominate these elements differently in different studies, they have been interpreted quite similarly—strict definitions appear in Section 3—[6,9,20,21]. The structural elements and their strong interrelation with energy system components is what motivated researchers to begin to use the TIS framework to study the energy sector's technological transition [6].

A global challenge such as climate change clearly needs multilateral solutions and agreements to manage the situation successfully [14]. Despite this need, few researchers have attempted to explore the origins of the drivers and barriers of RETs [11,14,21–25]. The studies aim to provide an understanding of the driving mechanisms behind emerging technologies, which helps accelerate progress in these technologies.

Scholars have argued that weaknesses[2] existing in any of the system's elements are imperfections that affect the performance of the entire system [6,11,27]. Hence, systemic barriers are worthy of investigation to resolve the problems they create. Such knowledge could be useful to justify government interventions [9] and to discover where such interventions matter the most [6]. To make headway in this subject, Woolthuis et al. [10] proposed a framework for system imperfections that includes: infrastructural failures, institutional failures, interaction failures and capability failures. Empirical analysis of each these components yielded their significance, and clarified suitable policies as possible solutions [9].

Likewise, scholars have attempted to explore systemic drivers for RETs to gain insight into why firms embark on innovation projects and how these projects become successful. According to the findings of such research, the reasons for launching innovation projects vary between identifying influential drivers of actors and society [14,28], recommending prosperous strategies [14,29], and finding the suitable policy framework [22,29,30]. Findings and theories on this subject are nevertheless somewhat inconsistent [15]. While the importance of multilateral drivers has been noted [14], no comprehensive study encompasses all drivers. Yet, this line of research has yielded the following list of commonly mentioned drivers:

- energy related policy [12,14,22,31],
- firms' pioneering activities [12,31,32],
- market demands and feedbacks [12,32],
- society awareness and preferences [14,22,31,32], and
- technological development and knowledge breakthrough [14,31,32].

Arguably, drivers and barriers are two sides of the same coin. Although despite sharing some characteristics, conspicuous distinctions exist between them.

3. Methodology

This study begins with an in-depth literature review followed by multiple-case study analysis. The chosen methodology enables the replication of the same proposition to gain a full picture of reality [33]. The study has two steps explained below to achieve its research aims.

[2] System weaknesses are also labeled "imperfection", "system failures", "system problems" and "weaknesses", among others in the literature. For more examples, refer to Negro et al. [9]

3.1. Literature selection method

To review significant literature on renewable energy, the first step is to identify relevant publications, definitions and keywords for RETs drivers. This review process yielded a first draft of a typology for drivers for RETs. Afterward, probing into the literature as well as secondary empirical data therein helped conceptualize this typology more comprehensively.

For the first step, a relevant set of a keyword searches in two primary search engines—Web of Knowledge and Google Scholar—was sufficient. The list of keywords used for the literature is as follows: technological innovation system; innovation system, drivers, motivators, technology push, renewable energy technology, RETs, development, progress, renewable energy, green energy, wind, solar, biomass, bioenergy, ocean, and wave.

Scanning titles and abstracts without necessarily spending much time reading full papers yielded a large pool of articles, from which 30 articles stand out as particularly pertinent to the research objectives. These papers meet two main criteria.

1) Due to study limitations both in terms of compatibility between the chosen markets and the ability to analyze large amounts of data, the scope of papers was restricted to the following countries and RETs.
   - EU-7 countries (UK, Sweden, Italy, France, Germany, Netherlands, and Spain) and Ireland. This consideration owes to ambitions and advanced RETs development processes in these countries.
   - Wind, solar, biomass and wave energy. The rationale behind this selection was to cover the three most mature sources of renewable energy (wind, solar and biomass) as well as wave energy as an immature but promising source. These cases, which are complementary aspects of the same phenomenon, provide a comprehensive theoretical picture.
2) When the subject matter of papers overlapped, the paper with the more comprehensive, broader contribution was selected for assessment. When the acquired data in selected articles were insufficient or articles were ambiguous in terms of data, additional sources we consulted and real case studies were examined in order to understand the rationale behind each driver.

3.2. Method of review

The review process started with the conceptualization of the typology of drivers. This consisted of combining the existing definitions of TIS structural elements (Section 4).

Subsequently, with drivers drawn from the literature review, the empirical data gathered from secondary academic sources yielded a database classified according to dimension, country of origin and technology. Having mapped the pattern of the drivers based on the technology and the country of origin, a discussion of the peculiarities of each case appears in Section 5. Finally, an iterative process of consulting the literature and referring to empirical data yielded a rich conceptualization of the drivers' typology.

4. RETs drivers

Evolution and interaction of the structural elements in TIS leads to the formation of a new system. These elements are the factors that may cause changes, advances or breakdowns in the system [6]. The importance of these elements can be understood by probing into the framework for the systemic barriers of RETs.

As previously discussed, Woolthuis et al. [10] identified five main categories of systemic problems. Whereas Woolthuis et al. [10] did not draw upon the structural elements of TIS to categorize the system barriers, Jacobsson and Bergek [6] posits the interrelatedness of the proposed categories and the structural elements of TIS. Bearing this in mind, in the current study, the structural elements are the main categories of RETs drivers (adapted from [6,16]).

Thus, RETs drivers are categorized, defined and conceptualized inductively and iteratively. The categorization started by defining the four structural elements of the system and one additional category as a source of drivers. This first step preceded the identification of inherent elements in each category.

4.1. Incentives for actors

Actors in a TIS may be individuals or organizations. This includes public actors (e.g., government), private actors (e.g., private firms throughout the whole supply chain), universities, research institutes, NGOs (e.g., consumer organizations) and influential stakeholders (e.g., venture capitalist) [5,16]. For a system to evolve, committed actors are essential at different system levels. This importance intensifies in the case of RETs, since even though transition might happen on a relatively small scale it affects a variety of stakeholders in different domains of society [5]. Therefore, "*for all actors involved in the decision making process the question of acceptability is at stake*" [34: p. 2628].

In this study, the RETs' drivers that originate in the actors dimension can be categorized into four groups.

4.1.1. Economic

The energy market is exceptionally capital intensive [31]. Hence, financial reasoning prevails in energy companies' decisions to engage in technological innovation. Holding a leading position in an energy market forces energy companies to plan their strategies with respect to market demands to maintain their profitability. Evidence of this is the reluctance of companies to engage in new technological projects with an absence of financial incentives [16].

Innovation is one of the main pillars of economic growth. Therefore, provided that there is a positive outlook concerning the future of a new technology, financial incentives are attainable. This is clear with RETs, since various sources cite their relative cost efficiency as one of the main drivers of energy firms' decisions to invest in such projects [6,24]. Unexploited potential and the knowledge available in the market lead to the crystallization of opportunities in profit and competitive advantage [22,23] through innovation. Notably, while progress in a given technology brings innovation to a system, innovation is associated with novelty in adaptation, organizational structure and other areas that all benefit a system as a whole [22].

4.1.2. Competences

Global competition implies that organizations must be able to operate successfully in diversified markets [35]. A company always risks losing its position due to the emergence of a new technology [9] or competitors [36]. Gaining new competences through investment in new technologies to counteract these threats is therefore a strong driver. Hence, competence incentives clearly affect the way that the market and its actors choose both old and emerging technologies [9]. Wüstenhagen and Bilharz [36] highlighted this phenomenon in the energy sector by introducing the ambition of differentiation as the strongest motivation for establishing RETs in both start-ups and incumbent utilities. Nevertheless, competences can be gained through different scenarios. These include the availability of pioneering entrepreneurs and experts [22], engagement in a demonstration project [22], acquisition of a new company [37], and gaining access to knowledgeable experts [38].

4.1.3. Targets

Targets are becoming significant drivers of innovative decisions in the energy system [39]. Government targets or those of the energy utilities themselves have bound actors' decisions and have shaped investment plans. At the present time, specified targets at the continental, national and firm levels have encouraged actors' ambitions to develop RETs. A clear example of this case is the European Commission's 2020 target [3], the speed of response to which has varied between countries [38].

4.1.4. Structure

Change acceptance within a system is another inherent characteristic that encourages RETs development [24]. Level of change acceptance could be analyzed at both the system and firm level. A flexible and cooperative system is more vulnerable to oncoming technical changes, while lack of flexibility in a system [6] or a firm [10] has been pronounced as one reason that hinders the viability of RETs. The Swedish experience with incumbent technologies (i.e., nuclear power) [6] and the global lock-in fossil fuel system [9] offer good examples of this situation.

4.2. Institutional incentives

Firms competing in the energy sector are inevitably influenced by their surrounding institutional framework [12,40]. The critical role of institutions in the energy sector [10] and ensuring that a new technology takes off [41] is widely acknowledged. Jacobsson and Bergek [6] states that, "*Firms are embedded in innovation systems that guide, aid and constrain the individual actors within them*" (Jacobsson and Bergek, [6], p. 817).

Despite its importance, scholars are divided in their views on interpretations of the concept of institutions. In 1990, North referred to institutions as the "*rules of the game in society*" [42]. This definition has been modified by Coriat and Weinstein [43] who state that if the institutions are the rules of games, then organizations are the players and they can impose change upon each other [43]. Generally speaking, institutions have been defined in two main ways. Firstly, they are defined as the contribution of regulations, policies and institutional theories. This type, which has been labeled hard institutions, encompasses all formal institutions and written regulations such policies and labor law. This includes technical standards, risk management regulations, safety laws, labor and employment laws, intellectual property rights and the general legal system [10,44]. The second type, "soft" institutions, refers to informal interfaces including norms and values of individuals, firms, organizations, regions and industries [9].

Institutional elements are thus categorized as a source of RETs drivers. For the sake of clarity, these elements are split into hard and soft institutions.

4.2.1. Hard institutions

4.2.1.1. Energy policies. Energy policies, including their impact on TIS formation, has been one of the most scrutinized topics in recent decades [6,7,45,46]. Political intervention is a key factor in technology transition in the energy sector [6,12]. The effectiveness of these policies depends on the following three attributes.

1) Policy formality: energy policies encouraging RETs development differ from country to country in terms of both type and level of support. Variations may arise in demand-side polices such as tax exemption, supply-side policies such as advanced cost-reducing schemes (i.e., feed-in-tariff, certificate system)

[36], and policies to facilitate the regulatory framework for authorization and permission procedures [6,22,38]. Thus, policies' supportiveness and effectiveness play an influential role on the progress of RETs.
2) Policy stability: the second driver of energy policies is associated with their long-term stability concerning a specific technology. The extent to which an energy company is convinced of constant and supportive energy policies undoubtedly affects its future planning. Clear examples of this are the highly successful development of wind and solar power in Germany [36] and Spain [24].
3) Policy conformity: regulatory frameworks in different regions and harmonization between them are also drivers of RETs. This uniformity, which promises a smooth development process, could exist at both the continental (i.e., across Europe) and national (i.e., between a country's regions) levels. The European Commission has emphasized the advantages of harmonization across Europe [47]. Nevertheless, energy utilities in Europe are still deploying divergent climate policies [48] and adopting different strategies and planning processes in different regions [49,50].

At the regional level, ensuring uniformity of regional policy and the consequences of this action demonstrates the importance of harmonization. The Spanish experience in the wind and solar power sector exemplifies this. Scholars have indicated that unconformity of regional policies has hindered RETs development and increased the difficulty for these technologies to break through [24].

4.2.2. Soft institutions

4.2.2.1. Market norms. Development of RETs is a long and uncertain process [2]. During this process, market norms can act as both a stimulus and a limitation, which can be characterized by the following:

- innovative entrepreneurs [51],
- entrepreneurial spirit [9],
- culture for shaping suitable public policy and regulation environments [44],
- trust and risk tolerance [10,51],
- willingness to share resources (i.e., other actors) [10].

Based upon their inherent features, market norms inevitably determine the extent of innovativeness and consequently the development of RETs.

4.2.2.2. Societal norm. Although academics have neglected to perform research into social norms, both as drivers and barriers, since the 1980s, their importance in the TIS formation is significant [34]. This importance is so great that society norms are proposed as the main explanation for varied development rate of RETs in different countries [52]. Social factors are often strong drivers of changes in energy markets. A clear example is the willingness of retail customers to pay more for electricity from renewable sources [36,53]. This interest in the society is what that motivated energy industry to accelerate adaptation of RETs [36].

At present, due to the society's positive opinion of RETs today, policy makers believe that social acceptance is no longer a barrier to development of RETs. In reality, however, the experience has revealed a different scenario [54]. Occasionally, opposition to the installation of new sites and facilities is an obstacle to developing RETs, such as is the case with the UK's experience of wind power development [22].

4.3. Network incentives

The third recognized structural component of TIS is associated with elements related to the system's network. Network refers to relationships between different firms, governments, knowledge institutions and third parties. These relations that have been interpreted as *orchestrated* are generally formed to solve a specific problem. This includes, standardization networks, public–private partnership, suppliers' partnerships and others [16]. On the other hand, networks with *less orchestrated* relationships are those describing relationships between firms and customers, buyers and sellers, industry and universities, social community, public associations, and research interest groups [16]. Within this context, while recognition of formal relationships is easy to explore, informal ones might require the identification of additional connections or sources [16]. Based on this knowledge, drivers of network dimension for RETs development can be subdivided to two main categories.

4.3.1. Strength of supply chain network

The first acknowledged stimulus group of this dimension is linked to the availability of essential actors and their interrelations in a network. As discussed, the energy system encompasses a variety of players. The actors range from suppliers and manufacturers to political authorities [22,25]. Although achieving cooperation between them may seem challenging, convenience of access and availability of all the required actors in a supply chain promises to be a successful system establishment. Effective and efficient interaction among system actors is found in a variety of processes such as network information [25], learning problem-solving techniques and competence sharing [10].

Overall, this category has formed one of the most dominant drivers and barriers in the system. While numerous scholars have posited a suitable strength of network connection as a driver in different settings [22,31,36], interactions that are too strong or too weak are among the substantial obstacles to a proactive system flow [9,10].

4.3.2. Societal networks

As discussed, social norms and the green movement within a society influence the awareness and preferences of agents in a system. This, therefore, stimulates private initiatives by society through the formation of independent associations, NGOs and communities as well as increasing the number of private customers. Results of this driver could be measured using an eco-labeling scheme by NGOs [36,55], private customers' investment in small-scale projects in their territories [9], non-residential customers' (i.e., government authorities), superior investments in green energy [36] and others metrics[3] that measure enhanced motivation at the system level.

4.4. Technological incentives

The importance of the technological dimension is clear from the title of TIS. Technology is an inseparable element of a technology-based industry. The contribution of technology as one structural element of a TIS is, however, dependent on the study's context and approach [6,20,56].

In this study, recognizing technological incentives is essential. This is due to the fact that technological progress and peculiarities have always been two of the main driving forces behind RETs development. Introduction of a new technology or improvement of an existing one may drastically change the functionality of an industry or a society [23,24,57]. Therefore, technological progress could be one of the main motives for managers to change their business logic or consider transformation [57]. When examining the motivators of the development of renewable energy, the contribution

[3] For more examples, refer to Wüstenhagen and Bilharz [36].

of the technological dimension is based on the following three categories.

4.4.1. Technology specifications

Both practicality and profitability of a technology are dependent on its status and maturity. Nonetheless, adaptation of a new technology requires significant effort and suitable timing, since arriving too early or too late to the market may change the future of a technological transformation [57]. This driver can be pinpointed in the development of the most mature type of RETs, namely wind power [24].

Additionally, RETs have their own stand-alone specifications due to their dependence on natural sources. These specifications make energy utilities' somewhat biased in their decisions regarding the development of each RET [24]. While technological maturity of a RET is an important element due to its direct impact on the technology's cost, generation capacity and practicality, the energy source (e.g., wind, solar, tidal) by itself influences the assurance of supply and the maximum generation capacity. This can be illustrated by the differences between natural qualities of tidal and wind power. While tidal energy is based on a reliable and fairly constant source of renewable energy, the more inconsistent wind transmission technology is the main source for the production of wind power.

4.4.2. Technology infrastructure

There is consensus that for companies to succeed, physical and solid knowledge infrastructures are essential [9,10]. These infrastructures effectively strengthen the foundation of an emerging system.

Physical infrastructure refers to technical structures that form the functional basis of a society including but not limited to: grid connection, ICT infrastructure, accommodation and facilities [9,10]. Evidently, energy companies' decisions on progression of RETs are dependent on these infrastructural factors [9]. Strengthening infrastructure would therefore add additional value and motivation to the system.

On the other hand, knowledge infrastructure encompasses elements such as knowledge, skills and training [10,44]. This category can contribute to enrich the existing knowledge in a network, inspiring perceptions of what is probable and favorable in the system; and therefore influencing network perception and the possibility of new system emergence. Jacobsson and Bergek [6] stated: "*Feedback loops from the formation of markets have influenced several other functions. Increased sales have generated growing resources for technology development in the capital goods sector and have also guided direction of search of new entrants into the field of renewable energy technology, bringing with them new resources.*" [12: pp. 825 – 826].

4.5. Regional incentives

In this study, regional incentives are the only stand-alone acknowledged dimension for RETs drivers that are not a structural element of TIS. Consideration of the regional dimension as one of the main dimensions of RETs drivers is due to the pivotal role of regional attributes on RETs evolution.

4.5.1. Regional attributes

Regional attributes are features inherent in the geography of a region in which a technology is planned to function. Such attributes can be influential in two distinct ways. Firstly, they determine the availability of a source of a RET in a region. Extensive coastlines to harness wave or tidal energy or large sunshine duration for solar power generation are clear examples of this factor.

Secondly, environmental vulnerability is another regional attribute which can influence a RET's future. Scientifically speaking, harnessing different source of renewable energy has some unavoidable side effects on both the biodiversity and ecology of an environmental system. These impacts might be that they interfere with the ecological system of a region and consequently with other regional industries such as agriculture. Thus, the current environmental status of a region and the existing industry are considerable influential factors in the evolution of a RET.

Fig. 1 provides the overall synthesis of the recognized dimensions and categories.

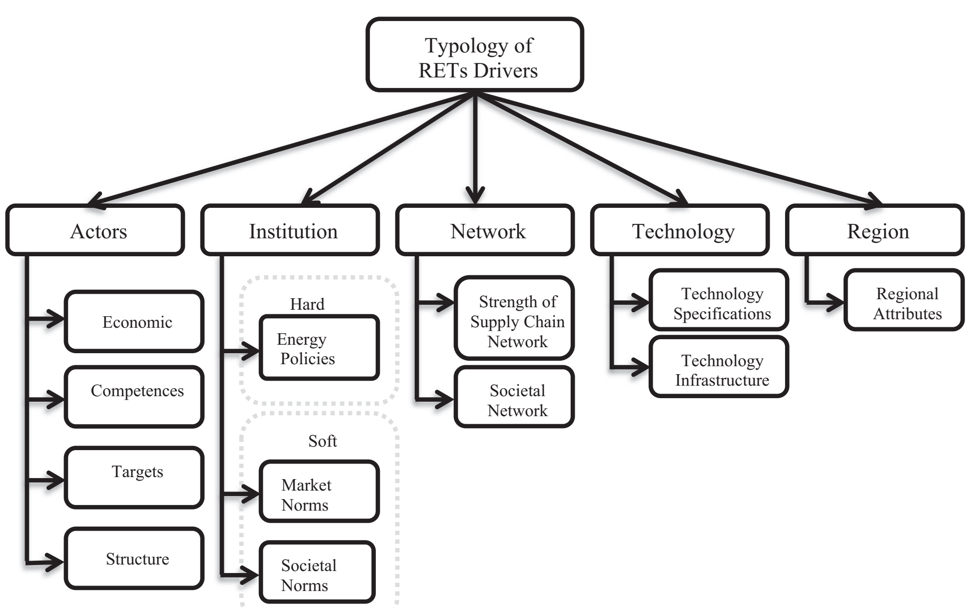


Fig. 1. The typology of RETs drivers within the TIS framework.

Table 1
Overview of drivers of RETs per country and technology.

Country	Energy source	Drivers						Reference
		Actors	*Institutions*		*Network*	*Technology*	*Region*	
			Hard	*Soft*				
United Kingdom	*Wind Energy*	Considerable number of project development (learning-by-doing)	Policy Support (granting site license; financial support; obligation certificates, quota scheme)			Technology advancement (on-shore)		[22,58,59]
	Solar Energy	Considerable number of project development (learning-by-doing); R&D effort; prospective market opportunity	Supporting policies (quota scheme; Specifically Funding)					[22]
	Biomass	R&D effort; high level of business risk acceptance	Policy support		Availability of all actors; availability of strong overseas developers; Active niche markets			[22,60,61]
	Wave Energy	R&D efforts	Policy support (funding – until 1999 – SRO3[a])				Potential resource	[22,25]
Ireland	*Wind Energy*		Policy support (tender system encouraging off-shore energy framework)	Established public support; awareness about dependency on depletable fossil fuel		Technology improvement	Potential resource	[32,39,62]
	Solar Energy		Policy pressure (Taxation)	Awareness about dependency on depletable fossil fuel		High potential of technology		[32,63]
	Biomass	Firms and farmers interest (e.g. additional income)		Environmental awareness (awareness about dependency on depletable fossil fuel)				[32,64]
	Wave Energy	Targets incentives	Policy Support (R&D funding, FIT[a]; encouraging off-shore energy framework; AER-3[a])	Public awareness	Public support (mainly funding); organization cooperation (universities and research center and research funding)		Potential resource availability	[25,32,39]
Sweden	*Wind Energy*		Policy support (certificate system with low certificate prices)	Positive public opinion		Technology improvement (cost reduction)		[62,65,66,12]
	Biomass	R&D efforts	Political support (additional funding, grant for switching to bioenergy; certificate system)	Governmental awareness (awareness and requirement of shift from nuclear power and imported oil); Public opinion (interest in environmentally cantered technologies)	Public opinion and activities (influential numbers of campaign)	Public activities and strong knowledge formation		[14,21,30,61,65]
	Wave Energy	Establishment of many research centers (e.g. wave energy research, Interproject service AB; Technoocean)			Cooperation between research centers(e.g. Wave energy research, Interproject service AB; Technoocean)		Potential resource	[25,39]
Germany	*Wind Energy*	Organizational effort to differentiate themselves, R&D effort; joint of farmers association; small companies lobbying	Policy support (FIT[a], EEG[a], Funding, supporting niche market); stable policy support	Public interest (green movement); social acceptance	Increasing rate of employment; STRONG manufacturing companies	Technology improvement (cost reduction)		[6,12,24,31,36,58,59,62,65]
	Solar Energy	Interested organizations (pioneering and lobbying activities)	Policy support (FIT[a], EEG[a])	Public Interest	Increasing rate of employment; strong network formation around this market	Technology improvement (cost reduction)		[36,63,65,67,68]
	Biomass	Joint of farmers association	Policy support (FIT[a], EEG[a])					[69]
	Wave Energy	R&D efforts in private companies			Cooperation of research groups and companies with off-shore engineering			[25]

Table 1
Overview of drivers of RETs per country and technology.

Country	Energy source	Drivers						Reference
		Actors	*Institutions*		*Network*	*Technology*	*Region*	
			Hard	*Soft*				
Spain	*Wind Energy*	Organizational competence (manufacturing competences, Pioneering entrepreneurs); Learning effects(R&D efforts); supporting financial institution (low investment cost)	Policy support (Taxation; Premiums; FIT[a]); Policy stabilities		Social Support (environmental NGO); Network support (Supporting Niche Market, strong manufacturing companies)	Technological improvement (cost reduction; learning and innovation)	Availability of energy sources	[24,31,62]
	Solar Energy	Strong PV industry (quality, innovativeness, commercial dynamic and flexibility)	Global institutional target (Koyoto protocol); supporting policies (obligatory installation of PV; FIT[a])	Social awareness	Increasing rate of employment	Technology improvement (cost reduction; competitive and innovative PV); technology attractiveness	Availability of energy sources	[24,70]
Netherlands	*Wind Energy*	Personal initiatives; Private financial supports	Policy support (TGC[a] system, subsidies and tax exemption)	Public opinion (Opposition to Nuclear power, society interest)		Technology improvement		[12,38,62]
	Solar Energy	Personal initiatives	Policy support (TGC[a] system, tax exemption)					[38,71]
	Biomass	Initiative and pioneer companies; (entrepreneurs, farmers association, public transportation)	Policy Support (regulation on water quality, TGC[*] system and tax exemption)	Existing motivation in private sectors of the society				[38,51,56]
	Wave Energy	Establishment of research groups (Teamwork Technology BV); R&D efforts in private companies						[25]
France	*Wind Energy*		Policy support (FIT)					[59,62]
	Solar Energy		Policy support (FIT)					[38]
	Biomass		Policy support (FIT, in progress)					[38]
	Wave Energy						Potential resource	[25]
Italy	*Solar Energy*		Partial policy support (FIT[a])					[63]
	Biomass	Organizational incentives (mainly forest owners both public and private and their intention of utilizing woods)	Policy support (certificate system); EU-policy forces		The project announcement by EU		Availability of biomass resources and massive agricultural lands	[61,72]
	Wave Energy	Research activity (Specifically University of Rome)			University and industry cooperation		Moderate potential resource	[25]

[a] SRO3—third Scottish Renewables Order; FIT—Feed-in-tariff; AER-3—Alternative Energy Requirement.

5. Implications for managing key technology

Building on research since 1990, this paper sets out a comprehensive typology for the drivers of RETs within the TIS framework (Fig. 1). Consequently, a cross-case comparative study was performed to reveal a full picture of the phenomenon and to explore and contrast patterns of each individual case [33]. To do so, a database was built containing all the drivers mentioned in the empirical data from the 30 papers that the literature review previously yielded. These drivers were then classified based on: (1) the driver's dimension, (2) the type of technology, and (3) the country of origin (see Table 1). The database was used for the following four tasks:

- to validate the consistency and comprehensiveness of the proposed typology,
- to explore if and why differences exist in the number and content of reviewed studies in different countries (Section 5.1),
- to perform a cross-case comparative study of RETs to explore the idiosyncrasies of each technology under study (Section 5.2.1),
- to conduct a cross-country comparative analysis exploring the diversity of drivers in different regions (section 5.2.2).

The discussion starts with a numerical overview of the database provided in Table 2. This summary, along with the numerical data, are presented in two columns, explained in detail below.

5.1. Numerical overview of reviewed papers

The first column of Table 2 is an indicator of the number of available and reviewed papers, corresponding to each technology in each country. In this column, while each row is an indicator of papers on each technology, the last row represents the total number of reviewed papers of a country. Notably, the total number is not merely calculated by the sum of the number of reviewed papers for each technology, because one paper may address two or more technologies in the same country. Accordingly, while the paper has been counted for each corresponding technology, its contribution in the total number is equivalent to one.

Table 2
Numerical overview of drivers of RETs per country and sector.

Country	Technology	Number of reviewed papers	Diversity of the drivers				
			Actors	Institution	Network	Technology	Region
United Kingdom	*Wind Energy*	3	1	4		1	
	Solar Energy	1	3	2			
	Biomass	3	2	1	3		
	Ocean Energy	2	1	2			1
	Total	6	7	9	3	1	1
Ireland	*Wind Energy*	3		4		1	1
	Solar Energy	1		2		1	
	Biomass	2	1	1			
	Ocean Energy	3		5	2		1
	Total	6	1	12	2	2	2
Sweden	*Wind Energy*	4		2		1	
	Biomass	5	1	5	1	1	
	Ocean Energy	2	1		2		1
	Total	10	2	7	3	2	1
Germany	*Wind Energy*	9	4	7	2	1	
	Solar Energy	5	1	3	2	1	
	Biomass	1	1	2			
	Ocean Energy	1	1		1		
	Total	14	7	12	5	2	0
Spain	*Wind Energy*	3	4	4	3	1	1
	Solar Energy	2	3	4	1	3	1
	Biomass						
	Total	4	7	8	4	4	2
Netherlands	*Wind Energy*	3	2	3		1	
	Solar Energy	1	1	2			
	Biomass	3	3	4			
	Ocean Energy	1	2				
	Total	7	8	9	0	1	0
France	*Wind Energy*	2		1			
	Solar Energy	1		1			
	Biomass	1		1			
	Ocean Energy	1					1
	Total	4	0	3	0	0	1
Italy	*Solar Energy*	1		1			
	Biomass	2	2	2	1		1
	Ocean Energy	1	1		1		1
	Total	4	3	3	2	0	2
EU7+Ireland	*Wind Energy*	14	11	25	5	6	2
	Solar Energy	13	8	15	3	5	1
	Biomass	14	10	16	5	1	1
	Ocean Energy	4	6	7	6	0	5
	Total	30	35	63	19	12	9

The results in this column indicate the heterogeneity of contributions in different countries and for different technologies. Primarily, on the basis of the findings, the highest numbers of contribution are recorded about the German market. This could be explained by this country's positive reputation in RETs development, which makes it an obvious target for scholars' attention. Germany is followed by Sweden and the Netherlands, where, although RETs development is less prosperous than in Germany, it is still considerable. This is understandable, since high-quality research on the relevant topics takes place in their local universities. The literature review indicates that investigations on the innovation system and innovation policies in these two countries are among the main drivers of research into RETs development.

On the contrary, the lowest number of contributions is about energy market of Italy, France and Spain. Even though share of renewable energy in France[4] or Spain[5] are considerable, academic research about these market is limited.

Secondly, the attention given to each type of RETs varies considerably depending on the technology itself and the country. Findings indicate considerable attention toward some technologies, and a lack of attention toward others. For example, whereas valuable literature on wind power is available in almost all the selected countries, there is an absence of robust studies on solar power development in four of the targeted countries (see Table 2). Similarly, biomass is among one of the most widely diffused RETs in Spain. Nonetheless, while some literature addresses the economic feasibility of biomass production [73] or technological options for bioenergy [74], there is no detailed study available on the systemic dynamics or drivers of this technology in Spain. These issues are worth considering in future research. The reason behind this lag (i.e., lack of scholars, lack of data, lack of interest in the region, etc.) could be an opportunity to gain a deeper insight in the regional industry and academia.

5.2. Cross-comparative study

The second column of Table 2 entitled “Diversity of the drivers” is representative of the diversity of identified drivers for each technology in each country. An illustration of how this number is calculated is as follows. For the development of wind power in the UK within the institution dimension, policy support has been mentioned as a driver through four types: (1) granting site license, (2) financial support, (3) obligation to obtain certification, and (4) quota scheme. Correspondingly, for each cell, reasons are counted and represented in the Table 2.

5.2.1. Cross-case analysis

Some authors have claimed that, “*to make renewable resources a major commercial reality is equated to putting man on the moon*” [75: p. 194]. Generally speaking, it takes about 50 years or more for a technology to be mature enough to cause a change in the energy market [6]. This is true of the development process of wind and solar energy, the most developed types of RETs. While initial development of wind and solar energy dates back to around 40 or 60 years ago respectively, huge efforts are essential to maximize their potential to meet renewable energy targets [6]. This period may be prolonged or reduced depending on the existing drivers and barriers, and the level of maturity of each RET. Findings indicate that not all the RETs received have the same amount of support in all countries. A visual representation of the data in

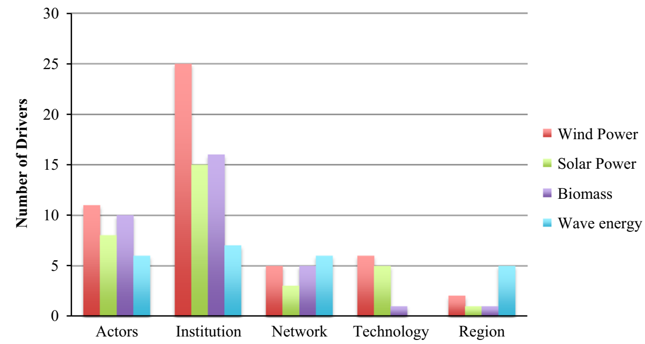


Fig. 2. Diversity of the drivers by technology and dimension.

Table 2 appears in Fig. 2, which illustrates the unequal role of each driver's dimension regarding each technology. This inequality has resulted in a varied rate of development for each technology in the countries under study (Fig. 3). How and why these timings depend on the drivers of each type of RETs is discussed below.

Indisputably, wind power is the most commercialized and commonly studied source of renewable energy in the RETs literature. Findings indicate that this level of maturity comes from receiving the most fervent support from all the elements in the system compared with other RETs (Fig. 2). Primarily, technological progress, practicality and cost efficiency of wind power technology is one of the main drivers for this RET [22]. This level of progress can be confirmed by the low price of generating on-shore wind power (86.6 USD/MWh),[6] particularly in comparison with the competing technologies such as advanced nuclear energy (108.4 USD/MWh) [76]. Due to this, even a small amount of political support and institutional practicality can make a huge difference in the profitability of this technology and make it a target for many profit-seeking energy companies. Thus, institutions have created great motivation to implement this technology. Supportive institutions are exemplified by the generous energy regulations of Germany such as the Renewable Energy Law (EEG). Under this legislation, wind power has been supported in a variety of arrangements [36]. In another example, Del Rio and Unruh [24] cited the supportive and stable regulatory framework of the Spanish government (e.g., Law of the Electricity sector, Plan for promotion of renewable energy) as a significant motivator for development of wind power production.

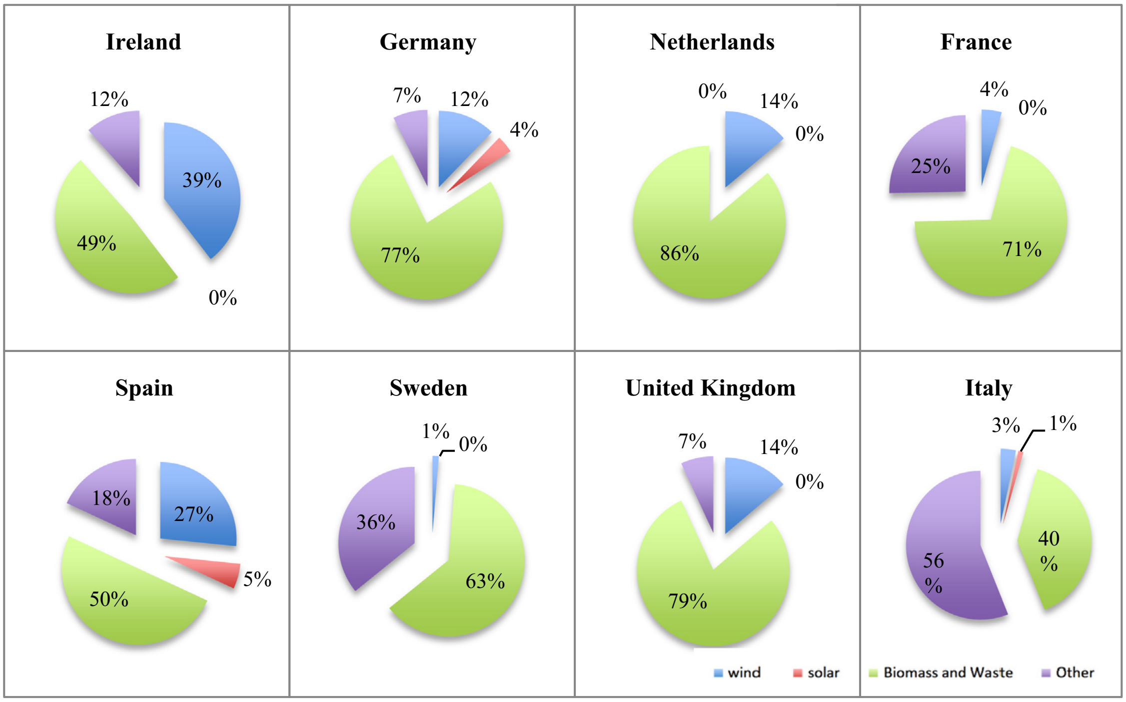
In addition, advances in wind power technology have led to the enhancement of knowledge and knowledge flow about this technology. As the result, actors became more motivated to cooperate with each other and, consequently, networks strengthened. These factors in conjunction form further system drivers [24]. Hence, development of wind power is supported by a variety of dimensions to the extent that its consumption may overtake currently prevailing conventional technologies (e.g., nuclear power) [77]. Barriers nevertheless still exist in the system. Examples of these hurdles are: the bureaucratic authorization process due to dense institutional structure in Spain [24]; inadequate promotional support and lock-in effect in the established system in Sweden [66]; energy policy instability in Italy [62]; or social opposition and shortage of skilled staffs in the UK [22].

Besides, differences exist between off-shore and on-shore wind power. As yet, off-shore wind technology is quite new and costly (221.5 USD/MWh) [76]. This cost marks the difference between off- and on-shore wind technologies. Nonetheless, although the

[4] This amount is 7.1% of the final gross inland energy consumption in 2010 (Source: Eurostat).

[5] This amount is 9.5% of the final gross inland energy consumption in 2010 (Source: Eurostat).

[6] Total system levelized cost corresponding to the per-kilowatt hour cost for construction, generation and operation of a plant in a specified period of time. For more detail refer to http://www.eia.doe.gov/oiaf/aeo/index.html.



Source: Eurostat

Fig. 3. Share of renewable energy in gross inland energy consumption per country in 2010 (%).

technology is still new, it is highly promising. Whether the existing market uncertainty toward this technology can be compensated by strong political support, regulation and grants remains to be seen [22].

Supported by multilateral drivers as well, solar power is ranked among the most attractive energy sources [36]. The availability of sunshine duration [24], technological improvement [63], solar based political supports [24,38] and, in particular, motivated actors [24,36] are among the factors impelling this technology. Despite this, a long-standing lack of technological improvement means that the cost of this technology is a major hindrance to its establishment [78]. Nonetheless, the prospect of solar power establishment by a variety of investors including private investors [71], as well as other big and small players [22], is slowly but surely pushing the development of this technology forward. The possibility for small, private players to establish solar power is what differentiates this technology from its counterparts such as wind power.

Yet, the high initial cost of solar power is a basic challenge (144.3 MWh for Solar PV and 261.5 MWh for solar thermal) [76]. Thus, supportive and stable energy policies are critical drivers for the development of this RET [24], a point that several studies on this technology have noted [22,24,39]. Nevertheless, a variety of barriers lead to slow adaptation. These barriers include unstable policies, lack of knowledge infrastructure and dissemination in Spain and the UK [22,24], or a low rate of sunshine duration in Ireland [32].

The contribution of actors in advocating biomass development is equivalent to the political framework [22,39,60,69]. This is due to the fact that farmers, forest owners and private firms have acknowledged biomass as a profitable source of income [56,69,72]. Therefore, biomass development has drawn interest from organizations and their internal activities, which have then accelerated development of this technology massively. This interest is strengthened by the political framework and its contribution to decreasing the cost associated with this technology (111.0 MWh) [24]. Nevertheless, despite the presence of profit-seeking actors, society's knowledge of this technology is poor [60]. Thus, this technology has lost ground to other RETs [60], which highlights the need for additional knowledge flow, pioneering activities and proactive companies to propel the development of this type of RET [56]. Additionally, to be more viable, other technology barriers including technology drawbacks [22], garnering sufficient policy support [79], and building network relationships [24] require improvement.

Analysis of wind, solar and biomass energy, the most mature RETs reveals that advanced development is unfeasible without support from multilateral drivers. While the importance of hard institutions has been pinpointed in the majority of relevant studies, this is insufficient as an isolated driver. Accordingly, besides political support, the development of a new technology, demands pioneering actors [6,14], support from societal norms [34] and advanced knowledge flow [56].

Historical development of wave power as an immature RET constitutes a rather different development scenario. In this technology, neither energy policy's nor actors' contribution is identified as more significant than others.

The first patent for ocean energy was registered as early as 1799 in Paris. The number of patents had increased to 340 by the end of 1973 [80]. This increase is an indicator this technology's promise. This potential and the readily available length of extensive coastlines is what motivated energy utilities to invest in research and development of this RET. This interest flourished, leading to an increase in the number of industries and supporting networks associated with this technology. Thus, this technology's potential, the availability of resources and motivated actors have created powerful drivers for the development of this RET [25]. Despite this interest, however, wave energy is still far from maturity needed to offer a competitive option for niche markets [25]. Additional technological development is an essential factor to disseminate the technology [22]. It is through the progress of wave energy technology and stable and supportive research grants from the government that this technology can reach its potential [25,39].

5.2.2. Cross-country analysis

As discussed, contributions from different driver dimensions differ between countries. Fig. 4, which displays the numerical data from Table 2 at the country level, depicts this information. As shown in Fig. 4, the group of countries is heterogeneous both in terms of the type and number of drivers appearing in the literature.

On the basis of our findings, the actors dimension is the most heterogeneous dimension of RETs drivers across countries. Actors' entrepreneurial activities and their decisions to engage in new RETs projects leads to a remarkable difference in development of RETs in different countries. Inevitably, actors' strategies and their flexibility determine types of opportunities they find in the market. This is clearly observable in actors' varying investment in climate projects or related research activities. This key role of actors may ultimately prove problematic; however, since barriers may form as a result of a lack of experts, diversity of actors, and their disparate goals or risk aversion.

The second heterogeneous dimension is associated with institutional factors, caused primarily by the hard institutions and less so by the soft ones. For a new technology to take off, therefore, the support of regulatory frameworks is essential and unavoidable [6,12]. All relevant studies, regardless of their geographical origins, have noted this dominance. Nevertheless, neither the amounts of support nor the types are similar in different regions. This has resulted in varying degrees of effectiveness of governmental promotional drivers [29].

For soft institutions, while governments believe that social barriers no longer pose an threat to the development of renewables, studies indicate the opposite [34]. Regional social perceptions influence the energy market distinctly in different regions. A clear example is the significant perception shift during 1984–2003 in Germany [36]. During this period, while people's faith in the practicality of wind power increased over the years, nuclear power lost popularity [36]. In a similar study in Sweden, a survey collected data on the desirability of different RETs. The results indicate that, although hydro and wind power are among the favored RETs, solar, followed by biomass, are the least preferred [60]. Thus, in spite of an absence of a clear sign of soft institutional barriers in countries like Germany or Sweden, these parameters play a contradictory role in Spain and the UK (for more detail please see Table 1).

The third heterogeneous dimension of RETs drivers relates to network factors. Networks are built via cooperative relationships that last through periods of development and design of products [9,10]. The relationships, which may be built between a set of system players during the emergence of a new TIS, have an impact on the efficiency and performance of the whole system. Clearly, however, neither market players' capabilities nor their availability is similar in different regions. This variation has accordingly resulted in varied rates of development in the countries under study.

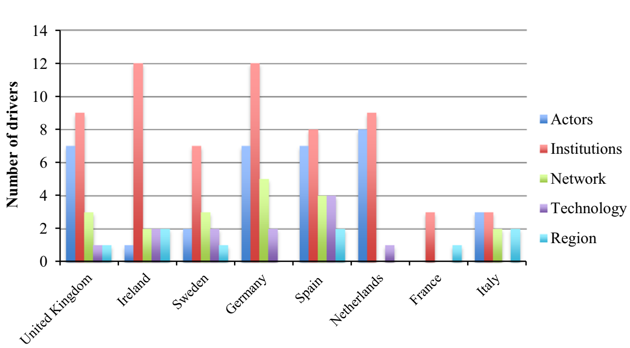


Fig. 4. Diversity of drivers per country and dimension.

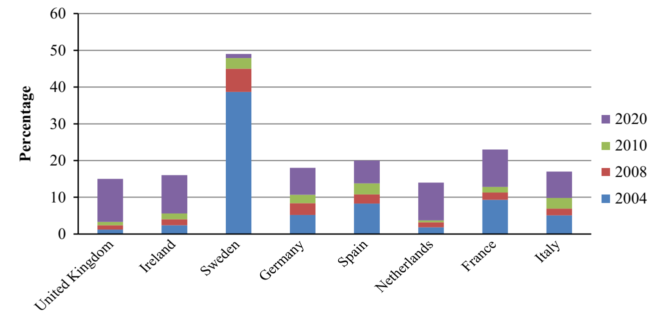


Fig. 5. Share of renewable energy in gross final energy consumption in the target countries.

On the contrary, regional features are identified as the least heterogeneous dimensions, followed by technological specifications. Predictably, technological progress of RETs influences the whole energy industry, regardless of the region. For instance, if a RET experiences a breakthrough and, as a consequence, the RET's production cost decreases, the whole energy industry may benefit. This is evident in the case of wind power and the competitiveness of this technology in the global market, due to this advanced technology's low production cost. In any event, technological infrastructure, as the second category of the technological dimension, forms the basis of the energy system. It is thus a necessity and so fewer variations are expected in this area.

For the regional dimension, features such as “exceptional coastline”, “low sunshine duration” and “windy heels” are commonly cited as the main driving forces for RETs development in different countries. This is anticipated based upon clear dependence of RETs on geographical conditions. If there is a possibility for a technology dependent on a natural source, regional features will come to the fore as key influential factors.

Heterogeneity among drivers is what causes the varied rates of development and consequently energy consumption from renewable energy at the country level (Fig. 5).

As shown in Fig. 5, Sweden, followed by Spain, displays the highest rate of energy consumption from renewable sources as of 2010. In the Swedish electricity market, the possibility of generating electricity from cheap sources with low emissions (i.e., hydro power and biomass) (Fig. 4), provided the country with a cheap and reliable source of energy, regardless of the level of support coming from energy-related policies [66]. Notably, this generation portfolio has led to a lock-in system, blocking the development of other emerging technologies [6].

In Spain, the plentiful availability of solar and wind sources and the high rate of greenhouse gas (GHG) emissions in the energy sector has driven the development of RETs [24]. The significant political initiatives, the green movement in the society and the pioneering actors all support Spain's wealth of opportunities to harness green energies. Nevertheless, despite the existence of drivers as well as the abundant availability of energy sources, RETs development in this country is still lagging behind Germany's [24]. This gap has widened in the wake of the financial crisis, which has destabilized the initially strong political support.

Fig. 5 shows that Germany and France occupy the next positions in the ranking. Germany has gained much recognition as the most successful nurturer of RETs. On the basis of our study, Germany received the greatest support from the different driver dimensions. Germany has initiated and strengthened this support through the differentiation of objectives of actors, capitalizing on the public backing of the green movement [62]. Strong networking and interconnection between actors and organizations are the outstanding elements of the German energy market [36]. This motivation has evolved into a sort of lobbying mechanism, which

has given rise to the emergence of new policies and a more suitable environment for establishing RETs [6,36]. The result of this establishment has led to the creation of a remarkable 12,000 jobs and €8.2 bn revenue for German enterprises [36].

In the United Kingdom, the political framework and pioneer actors have effected a change in the country's RETs market. As noted in the literature, however, the FIT system in place in the UK engenders a higher rate of risk for national actors, specifically versus peers (i.e., Germany) [81]. This has resulted in a failure in the technological transformation of this market, which now requires supplementary policy support [22].

Netherlands is another country where actors play a significant role as drivers. Interestingly, initiatives are led more by private investors and personal ventures than by corporate strategies. While initiatives are supported by a host of policies, the contribution of renewable energy to the Netherland's total energy generation is still minimal [71]. Notably, despite political support, doubt about the stability of the governmental regulations is considerable. The consequence of this doubt is the development of the most advanced RET, biomass digestion, in the Netherlands [9].

Finally, in Ireland the development of RETs is driven by awareness enhancement of the disadvantages of dependence on depletable energy sources including fossil fuels [32]. This awareness has received partial policy support, which allows actors to invest in emerging RETs. Despite this partial support, though, the contribution of drivers such as political support or technological infrastructure are still too marginal to bring about a change [32].

6. Concluding remarks

This paper posits a typology for drivers of RETs and empirically maps the drivers' significance, an issue which has gained inadequate attention so far. This contributes to the body of knowledge by providing an overall picture of RETs drivers. This knowledge aids understanding of where intervention is most effective, and provides a guideline for policy making if the EU targets for tackling climate challenges are to be met. Drivers are defined as factors that provide impetus to energy companies to embark on RETs development. Taking TIS as a valid framework for studying the energy system, drivers of RETs can be classified within the main structural components of TIS. These components are: actors, institutions, networks and technology. In addition, this study incorporates an additional dimension, region, to the analysis. The study explores and acknowledges 12 different categories of drivers within these five dimensions.

An in-depth conceptual and empirical literature review validates the proposed typology. For each technology, the literature yielded dominant drivers to build a database. A cross-case comparison of results reveals interesting timelines of the development of each RET. The comparative study confirms the influential role of both maturity level and country of origin on the development of each RET. The findings indicate that countries that nurture multilateral drivers enjoy a more successful development rate (i.e., Germany and Spain). Remarkably, while the importance of the political framework is mentioned in most extant research, this study's findings show that it cannot be the only driver. Thus, the contribution of the all elements in the system is necessary, which actors, especially energy companies, playing a key role. Actors' influence lies in their capacity to effect change in the political framework, competitive market, the evolution of emerging technologies and the strength of the system networks. Furthermore, although differences exist among RETs due to their technological specifications and the amount of support they receive, social perspectives, regardless of other parameters, determine the favorability of each RET. Overall, it is challenging, but critical, to develop an appropriate set of drivers as a tool for making progress in each technology.

This overarching study, despite its capacity to shed light on numerous issues related to RETs, does have some limitations. First, the proposed typology still requires deeper conceptualization in some dimensions to be fully inclusive. Nevertheless, this is the case for many others studies such as the framework for system barriers proposed by Woolthuis et al. [10]. Secondly, even though an exhaustive literature review has ensured the inclusion of the vast majority of important, pertinent materials available within the academic literature, this study only focuses on academic papers. This limitation can be addressed in future studies focusing on different categories of RETs drivers and analyzing advantages and disadvantages associated with each category for different technologies and different countries.

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